MTF-Derived Image Metric for the Performance of Laser-Based Imaging Systems

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LONG-TERM GOALS

Modeling of the performance of laser-based imaging systems has progressed to the point where simulated images are being produced and compared against actual imagery from these systems. For a researcher, this is the ultimate assessment tool by which to predict the performance of a particular system, as well as to compare the performance of different systems in ocean waters characterized by the same optical properties. These simulated images can be visually compared side by side for two competing systems such as the Laser Line Scanner (LLS) and Streak Tube Imaging Lidar (STIL).

However, from a mission planning perspective, where decisions have to be made about the deployment/nondeployment of a system within an area of interest to the Navy, what is needed is a simple scalar metric of image quality. This is in direct analogy with the concept of signal excess for Navy sonar systems as the scalar metric for sonar performance in ocean waters characterized by range-dependent sound speed profiles.

The goal of this effort is therefore to come up with a scalar image metric which would best describe the expected image quality of laser-based imaging systems before actual deployment, thereby providing Navy personnel a basis on which to decide whether or not to deploy a system. Such a scalar image metric could be evaluated along a planned reconnaissance track for the optical conditions expected at deployment time, and that information could be used by Navy personnel to make a final go/no-go decision about deployment.

OBJECTIVES

The performance of laser-based imaging systems such as LLS and STIL is not noticeably different in clear ocean waters, where the main differentiators are system design and noise. Technological breakthroughs and improvements in electronics are gradually eliminating system noise as a deleterious effect on image quality.

In littoral waters of importance to the Navy, however, the performance of laser-based imaging systems is affected mostly by the optical environment in which they operate. Indeed, the overall goal of system designers is to find the best system configuration which will mitigate against the deleterious effects of the environment on the acquired image: forward scattering, backscattering and photon noise. The latter becomes important when the number of photons accumulated at a "pixel" over the system integration

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14. ABSTRACT
Modeling of the performance of laser-based imaging systems has progressed to the point where simulated images are being produced and compared against actual imagery from these systems. For a researcher, this is the ultimate assessment tool by which to predict the performance of a particular system, as well as to compare the performance of different systems in ocean waters characterized by the same optical properties. These simulated images can be visually compared side by side for two competing systems such as the Laser Line Scanner (LLS) and Streak Tube Imaging Lidar (STIL).

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time is less than a few hundred. This is a natural fluctuation in the received intensity which is due to optical scattering and absorption. The main objective of this effort is to characterize image quality as a function of the optical environment in which systems will be deployed by incorporating forward scattering, backscattering and photon noise into an image scalar metric. The image metric selected as a result of this effort will be chosen with respect to its potential use as input to tactical decision aids to be used by mission planners.

APPROACH

Image metrics for classification/identification of features in an image already exist in the atmospheric reconnaissance community. This community uses the National Imagery Interpretability Rating Scale (NIIRS) as an image metric. The NIIRS has a value between 0 and 9, with 1 representing the ability to distinguish between major land use classes and 9 the ability to detect individual spikes in railroad ties (see reference 1). Generally speaking, the more information extracted from the imagery, the higher the NIIRS rating. As pointed out in reference 1, "separate military NIIRS scales have been developed for visible, infrared, radar and multispectral sensor systems because the exploitation tasks for each sensor type can be very different". The drawback in applying the NIIRS approach as an image metric for underwater laser-based imaging system performance is that it does not incorporate the effect of the optical environment on image detail, the limiting factor for imaging in the turbid conditions found in littoral waters.

Metrics such as signal-to-noise ratio (SNR) and contrast become inadequate when trying to quantify the detailed information present in an image, such as needed for classifying or identifying an object. Classification/identification of an object involves imagery that has information about the spatial frequency content of that object. Spatial frequency is a measure of the repetition of features in the image and can be associated with level of detail: high spatial frequencies correspond to fine detail in the image.

PSI has therefore investigated an image quality metric based on the Modulation Transfer Function (MTF). The MTF describes how the spatial frequencies in an image are affected by both the system optics and electronics as well as the underwater optical environment. There is therefore a direct relationship between the quality of an image and the shape of the MTF curve. An effort has also been made to incorporate a system's ability to mitigate against the deleterious effects of the underwater optical environment.

In another approach to describing image quality for reconnaissance missions, Jensen (see reference 3) derived the atmospheric modulation transfer function due to the path radiance between observing platform and the ground:

$$MTF_{veil}(R) = \left[1 + \frac{L_P(R)}{L_{scene}^{avg} e^{-cR}}\right]^{-1}$$

where $L_P(R)$ is the path radiance, L_{scene}^{avg} is the average scene radiance, R is the distance between platform and the ground, and c is the total attenuation coefficient of the atmosphere. The scene he considered was a repetitive luminance pattern consisting of a series of black and white stripes. It can be seen that the modulation transfer function is unity when the path radiance is negligibly small.

Jensen's above formulation can be generalized to include the effects of forward scattering. Although his equation includes scattering through the extinction coefficient *c*, it does not address the phenomenon of photons being scattered to neighboring pixels. For a repetitive luminance pattern, forward scattering of photons would result in the white stripes diminishing in intensity while the black stripes would increasing in intensity, thereby resulting in a lesser modulation of the striped pattern.

The MTF derived by the PI which includes the effect of forward scattering and the veiling effect of the path radiance can be expressed as:

$$MTF_{total}(\psi, R) = MTF_{scat}(\psi, R) MTF_{veil}(R)$$

where

$$MTF_{veil}(R) = \left[1 + \frac{L_P(R)}{L_{scene}^{avg} e^{-(a+b_b)R}}\right]^{-1}$$

and $MTF_{scat}(\psi, R)$ is the modulation transfer function for forward scattering. Several functional forms exist and the Wells analytical formula was chosen as a starting point:

$$MTF_{scat}(\psi, R) = e^{-b_f R\left[1 - \frac{1-e^{-2\pi\theta_o\psi}}{2\pi\theta_o\psi}\right]}$$

where $\psi = \nu R$, b_f is the forward scattering coefficient and θ_o is the mean scattering angle. The main differences with Jensen's derivation are the $MTF_{scat}(\psi, R) e^{-(a+b_b)R}$ term in the numerator and the $e^{-(a+b_b)R}$ in the denominator, where *a* and b_b are the absorption and backscattering coefficients, respectively.

WORK COMPLETED

A review of the literature concerning image quality metrics was performed. Although in wide use in different scientific fields, the NIIR approach was found inappropriate when the major deleterious effects on imagery are due to the optical environment itself. As shown in the last section, the PI derived a general formula for the MTF of the optical environment.

A new image quality scalar metric was defined with the help of this MTF. As pointed out by Biberman (see reference 4), the Modulation Transfer Function Area (MTFA) is "the summary measure of image quality which shows the greatest promise for meeting" the following criteria:

1. easily measured for existing imaging systems,
2. quantitatively predictable, analytically, for future imaging systems at the paper design stage,
3. highly co-empirically determined operator performance under the operational conditions of interest related with the specified mission.

In order to obtain an image quality scale from 0 to 10, the metric proposed by the PI for contrast-limited imagery is defined as ten times the normalized MTFA. The normalization factor is the area between the MTF and the threshold contrast curve when it is equal to 1.0 for all spatial frequencies. The threshold contrast curve serves to include the human observer into the value for the MTFA. For noise-limited imagery, the threshold contrast curve is replaced by the “demand” function (see reference 2), which is the minimum modulation necessary to detect a sinusoidal pattern as a function of spatial frequency for a particular average image signal-to-noise ratio (SNR). In general, the necessary modulation increases with spatial frequency and decreases as SNR increases.

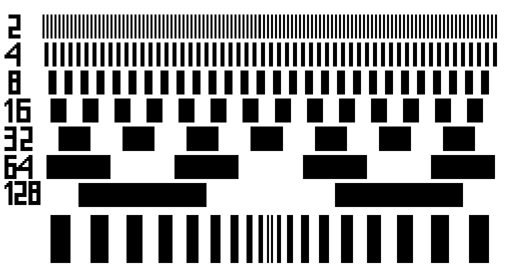
For contrast-limited imagery, an interactive GUI was created to allow the user to introduce gradual changes in the optical environment and to correlate the proposed image metric correlation with image quality. For noise-limited imagery, an investigation of the magnitude of the proportionality constant involved in the relationship between this demand function, spatial frequency and SNR was begun by creating an interactive GUI which allows for the simulation of Poisson distributed pixel noise and the control of a sinusoidal pattern with adjustable modulation.

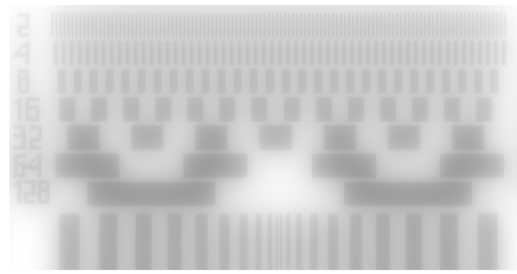
RESULTS

The effect of the optical environment on the quality of imagery acquired by a “perfect” camera was simulated with the help of a contrast panel (top left of Figure 1) containing black and white bars of unit modulation for all spatial frequencies. The contrast panel is 256 by 256 pixels and the numbers on the left hand side is the number of pixels occupied by a black/white pair of stripes. The target size is assumed to be 1 meter for the simulation and to be located 5 meters from the camera.

Note that the picture on the lower right shows the same effect with the magnitude of the path radiance adjusted so that the image metric is equal to .500. This is the same value as in the previous forward scattering illustration at the top right and shows that the image metric magnitude is consistent as far as information extraction is concerned. The spatial frequency labeled 2 is just as hard to discern in both cases, while the lower spatial frequencies are still discernible.

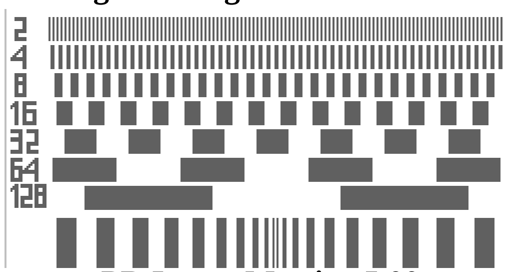
Figure 2 shows the effect of another phenomenon due to the optical environment. Photon noise is the term associated with the natural fluctuations in the number of photons collected over the integration time of the camera. These fluctuations follow Poisson statistics where the signal-to-noise ratio varies as the square root of the mean number of photons collected. The spatial frequency labeled 2 is now hard to discern. One can see that the lower spatial frequencies are more discernible and that a lesser modulation is therefore needed to discern them. As previously discussed, these are the characteristics of the “demand” function which is proportional to frequency and inversely proportional to SNR. The determination of the appropriate proportionality constant is the goal of this SNR simulation.





Original Image Metric = 9.90

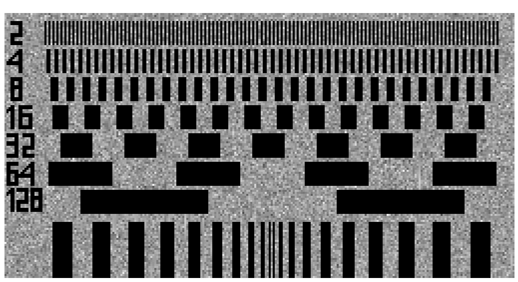
FS Image Metric = .500



PR Image Metric =5.00

PR Image Metric = .500

Figure 1. Effect of environment on image quality of a contrast panel consisting of horizontal lines of black and white bars with their separation gradually increasing from top to bottom. [The original unaffected image is at the top left. The effect of forward scattering (FS) for 3.5 scattering lengths is shown in the upper right image where the very closely spaced bars are blurred to the point where the striped pattern cannot be discerned. The bottom two images show the contrast loss due to the path radiance (PR) between target and camera. The loss is the same for all separations. The lower left image has the path radiance equal to the average target radiance. The contrast loss is more pronounced in the lower right image where the path radiance was increased significantly.]



SNR = 5.00

SNR = .100

Figure 2. Effect of low level signal on image quality of the contrast panel. [The picture on the left shows the target when the SNR is equal to 5.00, a number suggested in the literature as a threshold for detecting contrast between neighboring pixels. The picture on the right shows the deleterious effect of photon noise for a SNR of .100. The most closely space balck and white bars are hard to discern. The lower spatial frequencies are gradually more discernible and that a increasingly smaller modulation is therefore needed to discern them.]

IMPACT/APPLICATIONS

The development of an image quality metric based on the expected optical properties of littoral waters will have a direct impact on mission planning and deployment of electro-optical imaging systems.

TRANSITIONS

Results from this effort should be used by mission planners and Navy personnel involved in the decision-making process for the deployment of laser-based imaging systems which will be in the Fleet in the near future.

RELATED PROJECTS

This effort is directly related to the modeling of the performance of laser-based systems of interest to the Navy.

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